Unsteady Heat-Flux Measurements of Second-Mode Instability Waves

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Introduction

- Atomic Layer Thermopile (ALTP) sensors
  - Developed by Tim Roediger (2010 Doctoral Thesis, University of Stuttgart, Germany)
  - Provides a time-resolved heat-flux measurement
  - Good spatial resolution: ~1 mm^2
  - Frequency response on the order of 1 MHz
  - Linear static response over several orders of magnitude (from mW/cm^2 to kW/cm^2)

- Well suited for measurements of unsteady heat transfer in a wide range of flow problems
  - Heat transfer in turbomachinery
  - Stagnation point heating
  - Shock-boundary layer interactions
  - Measurements in short duration supersonic and hypersonic facilities
  - Laminar-to-turbulent transition

Objectives

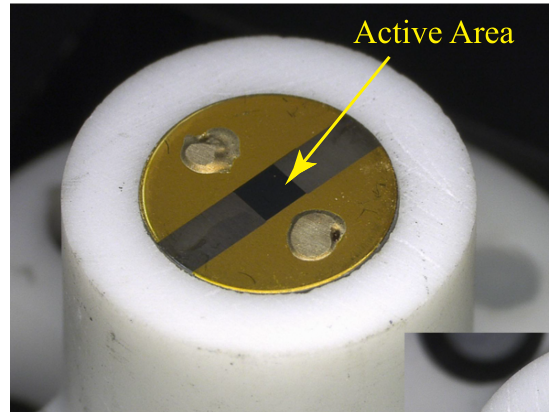
- Gain experience with the ALTP sensors for measurements in transitional hypersonic boundary layers
  - Previous work by Roediger *et al* (2009), Roediger (2010), and Heitmann *et al* (2010) demonstrated this application in short-duration hypersonic wind tunnels
  - Demonstrate application in our conventional hypersonic blow-down tunnels

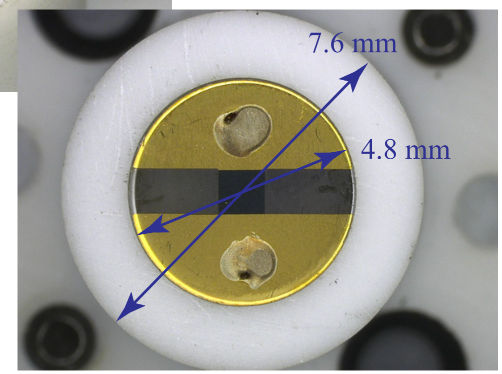
- Develop the capability to dynamically calibrate the ALTP sensors
  - Measurements of the sensor frequency response function
  - Critical for cross-correlations and cross-spectral analysis with multiple sensors

- Measure second-mode instability waves on a flat plate model in a Mach 6 freestream flow

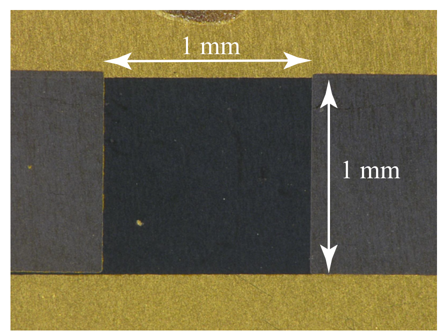
Atomic Layer Thermopile (ALTP) Sensors

- Sensor area of 1 mm^2
- Nominal bandwidth of ~1 MHz
- Nominal static sensitivity of 48.0 $\mu V/W/cm^2$
- Signal from ALTP sensor is amplified with a miniature amplifier placed inside the model
  - AC coupled signal has a fixed gain of 5000 and bandwidth from 17 Hz to 1 MHz
  - DC coupled signal has adjustable gain from 100 to 800 and a bandwidth of 100 kHz



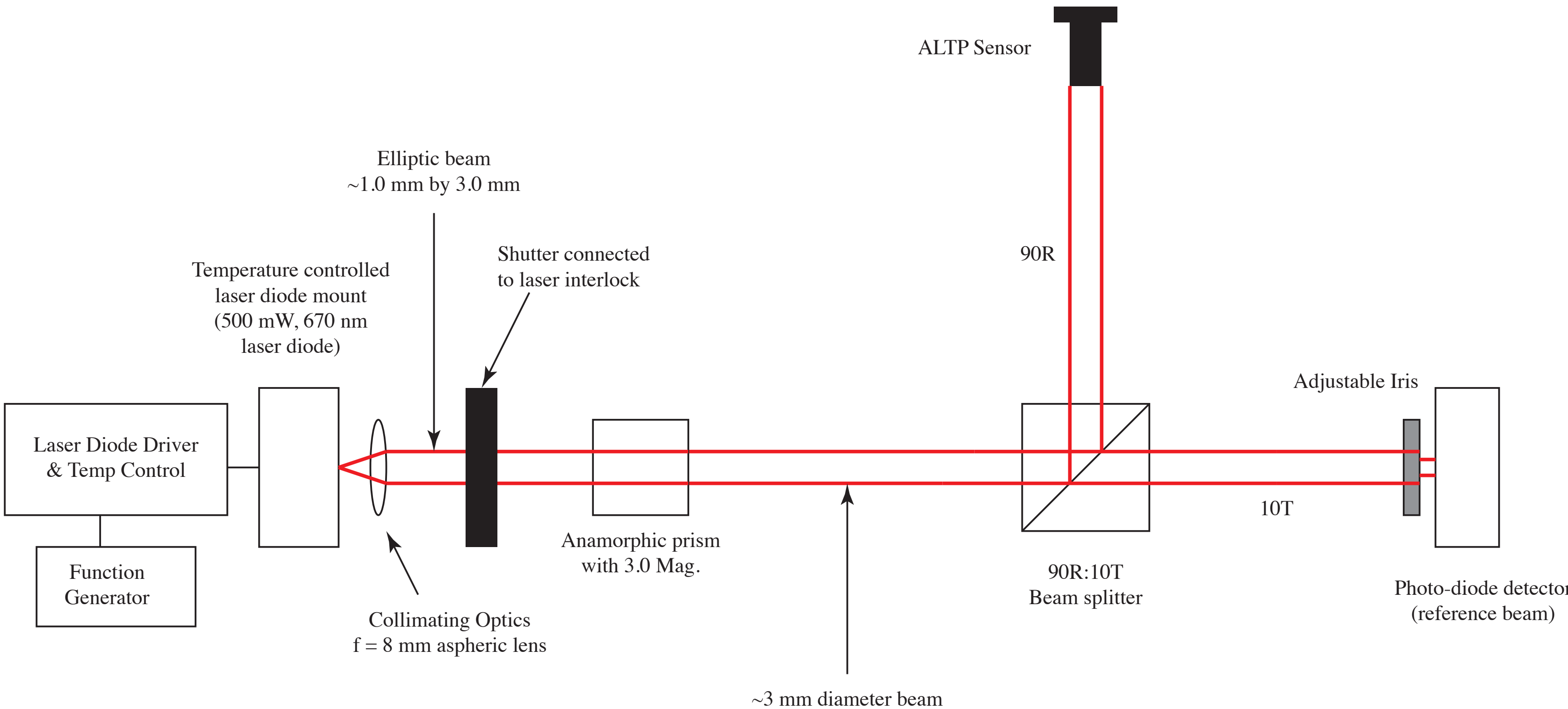


Perspective and top views at 30X optical mag.

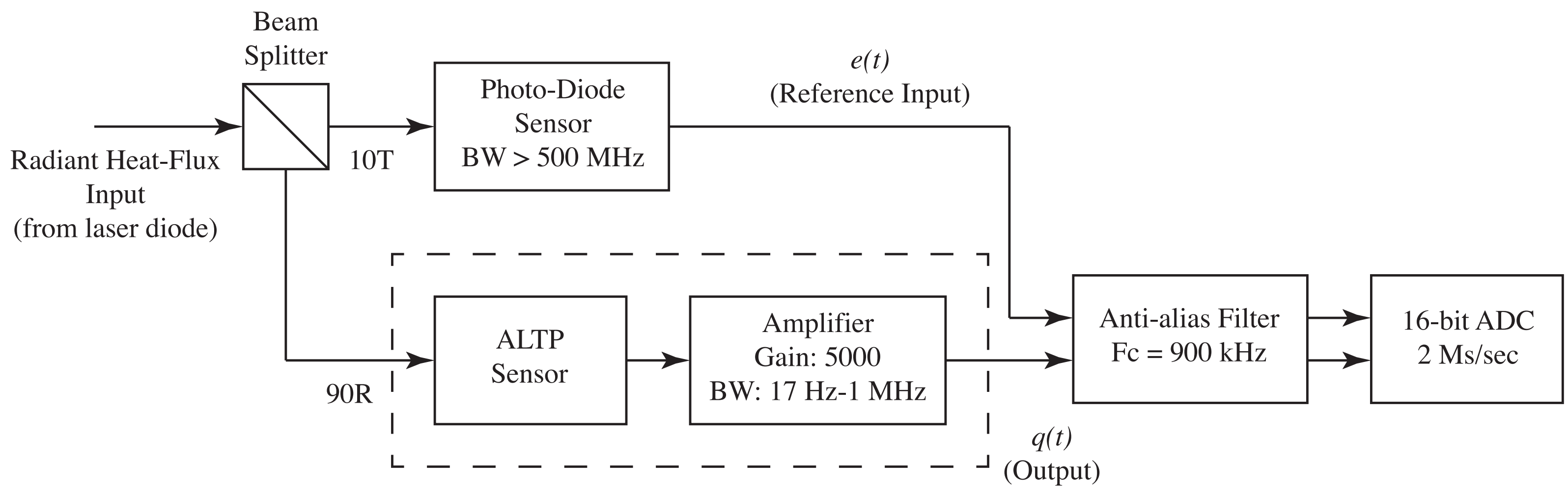


Close-up view of sensor active area at 150X optical mag.

Experimental Setup for Dynamic Calibration of the ALTP Sensors



Frequency Response Measurement Details



- Amplitude modulate radiant heat-flux input with a sine wave
- Collect time-series data for a range of sine-wave frequencies
- Calculate the frequency-response function between the reference input measured by the photo diode and the output of the ALTP sensor amplifier

$$H(f) = \frac{G_{xy}(f)}{G_{xx}(f)}$$

$|H(f)|$ Magnitude

$\angle H(f)$ Relative Phase

Acquisition and Processing Parameters

$F_s = 2\ \text{MHz}$

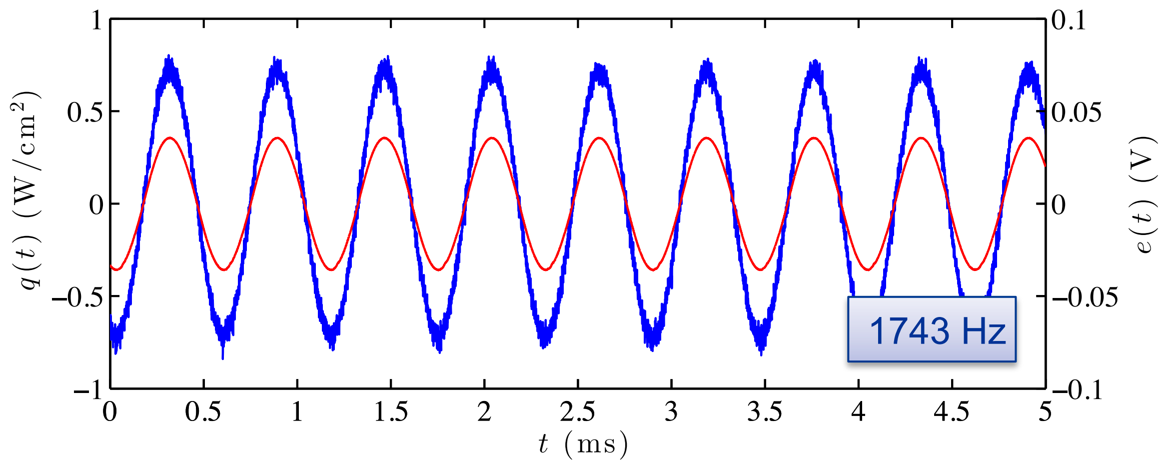
$N_{samp} = 4 \times 10^6$

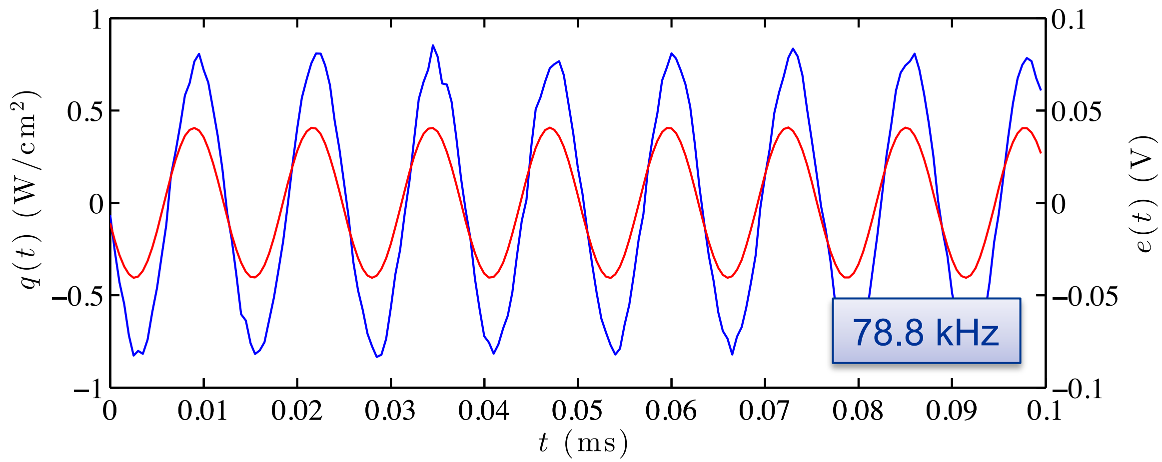
$N_{fft} = 50000 \qquad N_{blk} = 160$

Hanning Window, 50% overlap

$\Delta f = 40\ \text{Hz}$

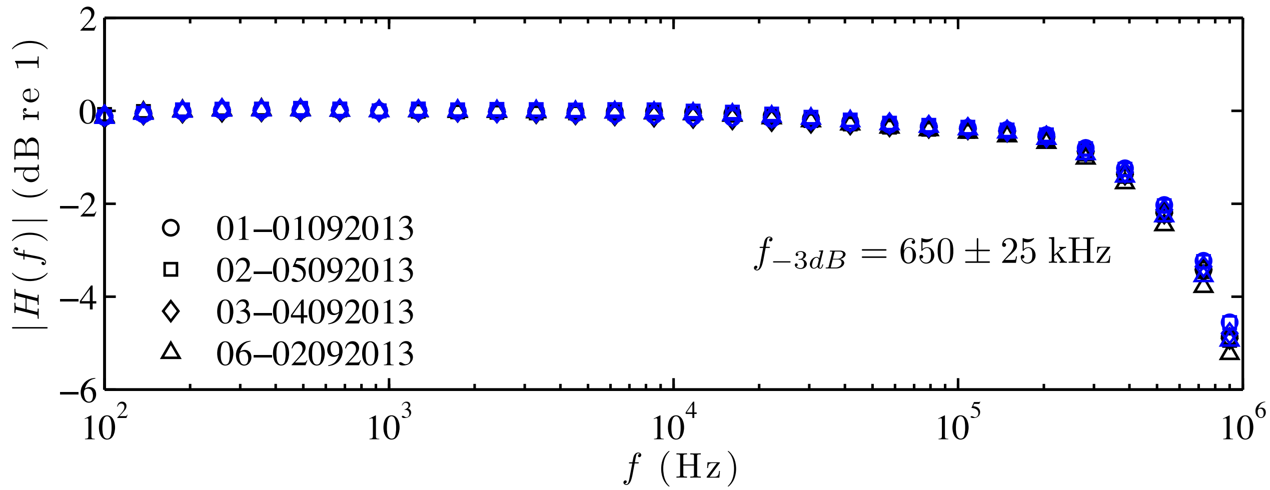
Sample Time Series Data for Dynamic Calibration

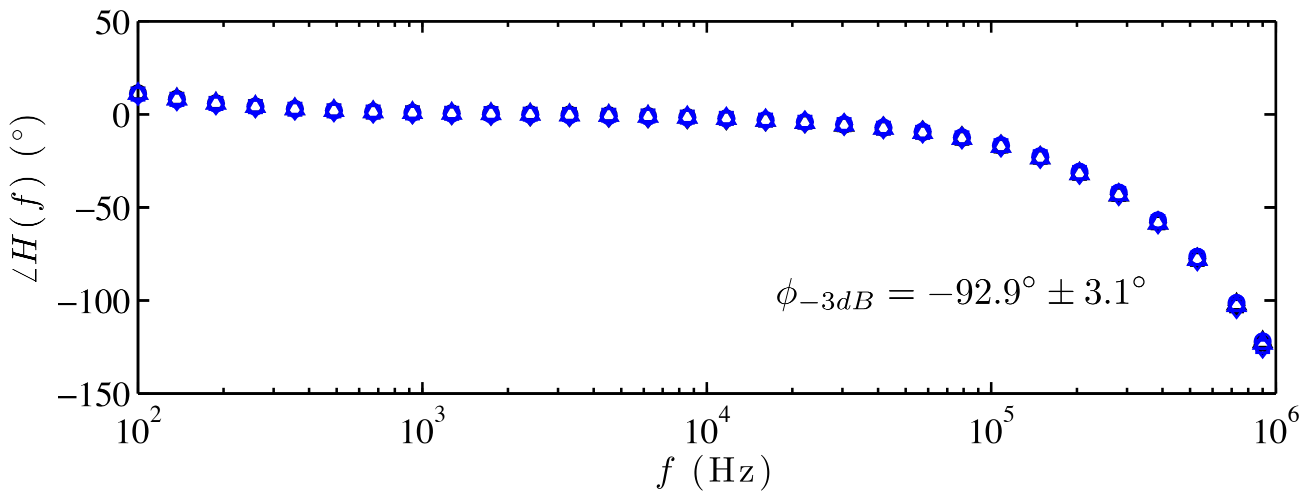




Red Curve: Reference Photodiode
Blue Curve: ALTP Sensor

Frequency Response of ALTP Sensors

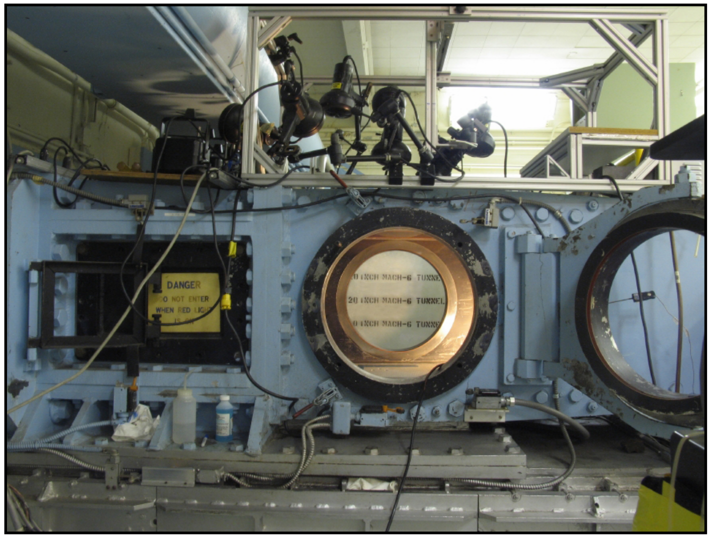




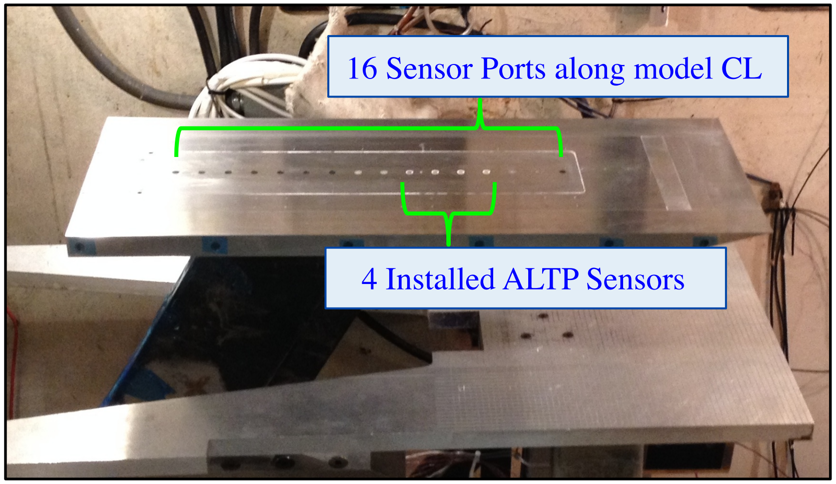
Black Symbols: Pre-Test Measurements
Blue Symbols: Post-Test Measurements

Experimental Setup

- Facility
  - Langley Aerothermodynamics Laboratory 20-Inch Mach 6 Tunnel
  - Conventional blow-down tunnel
  - Test Gas: Air
  - Re Range: 1.6 to 28.5×10^6/m
  - Total Temperature: 465 to 520 K

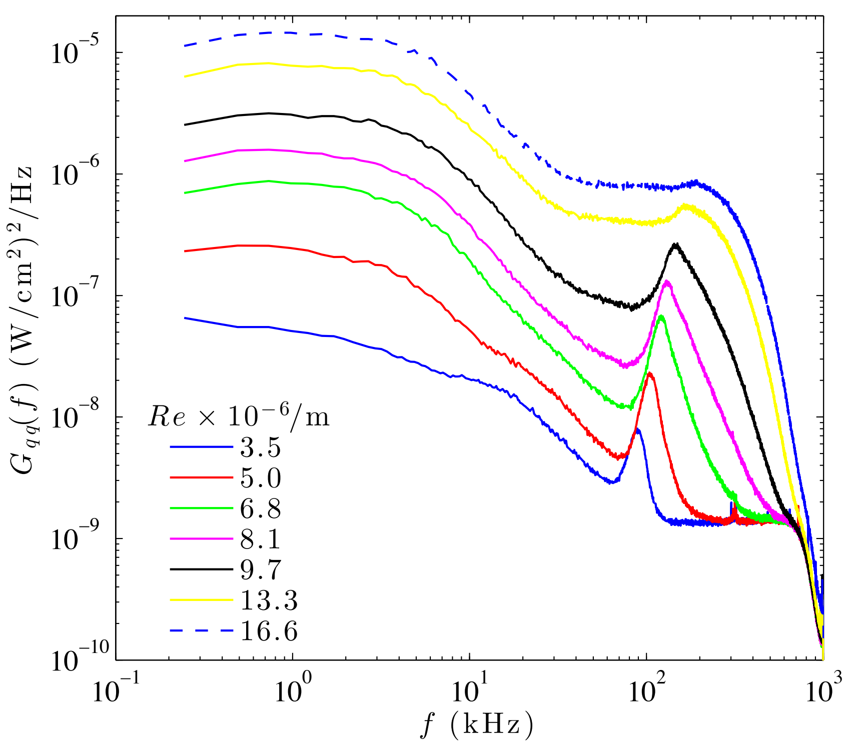


- Flat plate model
  - 71.12 cm long by 27.94 cm wide
  - Sharp leading edge
  - AOA of zero and -5 degrees
  - ALTP sensors were mounted in a streamwise array along model centerline
  - 16 sensor locations were available from x = 21 cm to 63 cm with 2.8 cm spacing
  - For a given run, 4 ALTP sensors were installed

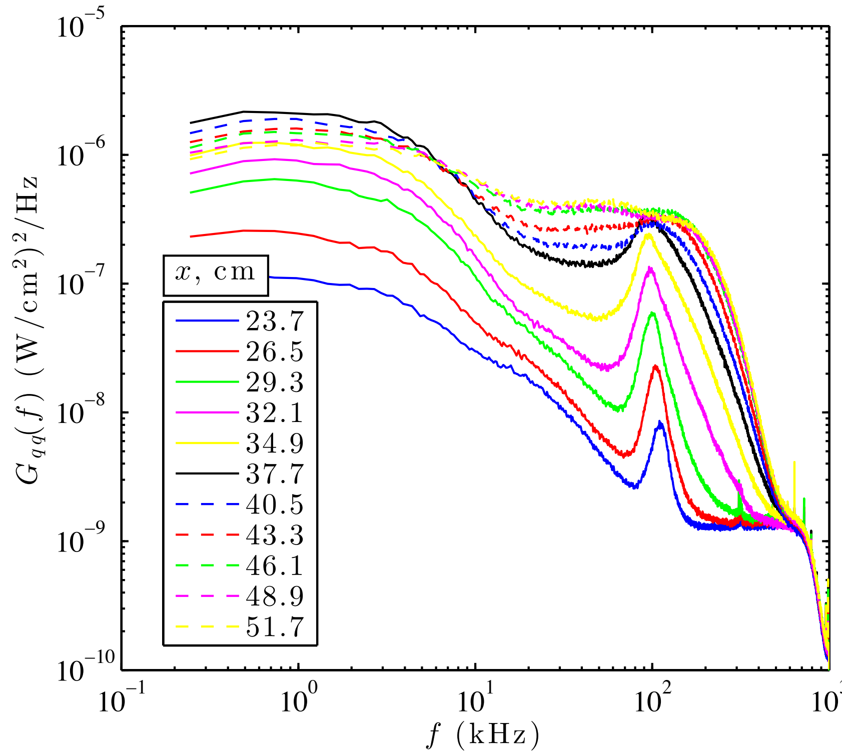


Heat Flux Power Spectral Densities

Heat Flux Power Spectral Densities at x = 26.54 cm for a range of freestream unit Reynolds numbers and an AOA of zero degrees

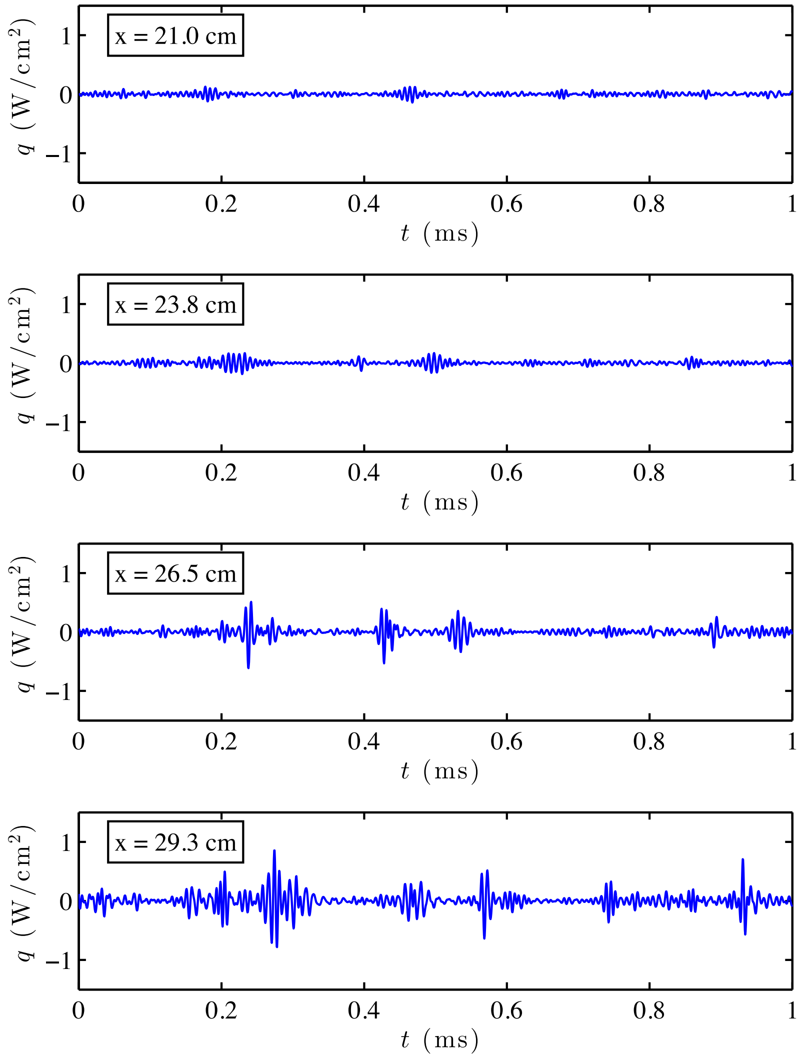


Streamwise evolution of heat flux power spectral density at a unit Reynolds number of 5 million/m and an AOA of zero degrees



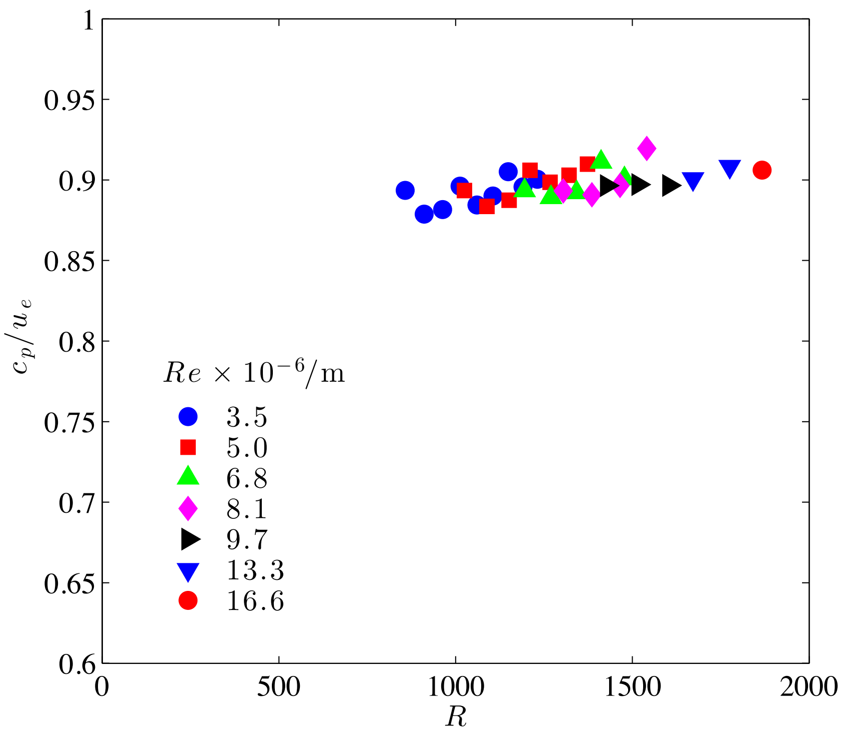
Sample Heat Flux Time Series

- Heat flux time series at several streamwise positions acquired simultaneously during a run
- Time series were band-pass filtered about the most unstable second mode frequency (70 to 200 kHz)
- Unit Reynolds number of 8 million/m

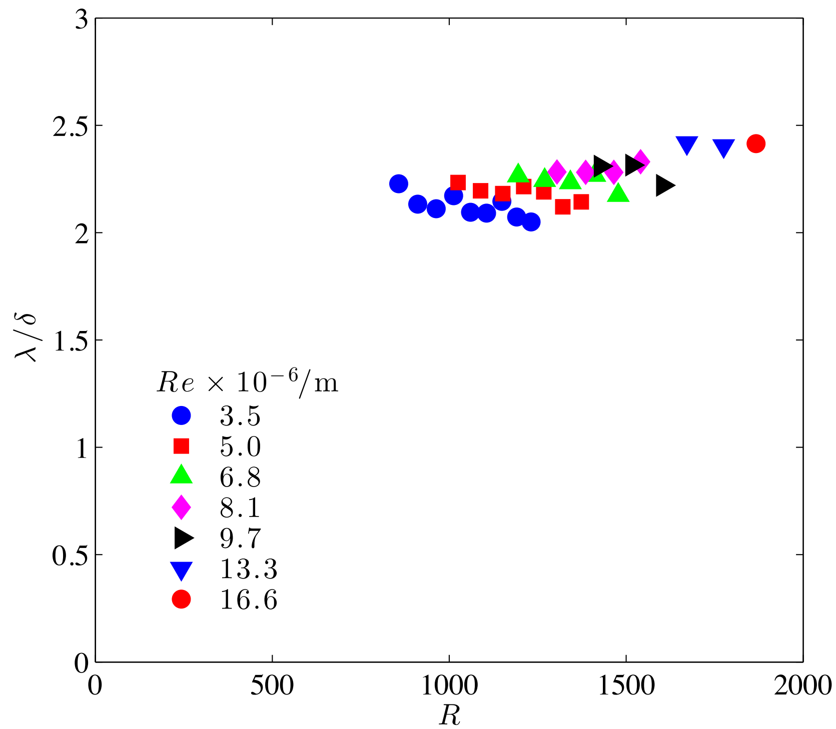


Second-Mode Wave Parameters

Measured phase speed for the most unstable second-mode disturbances



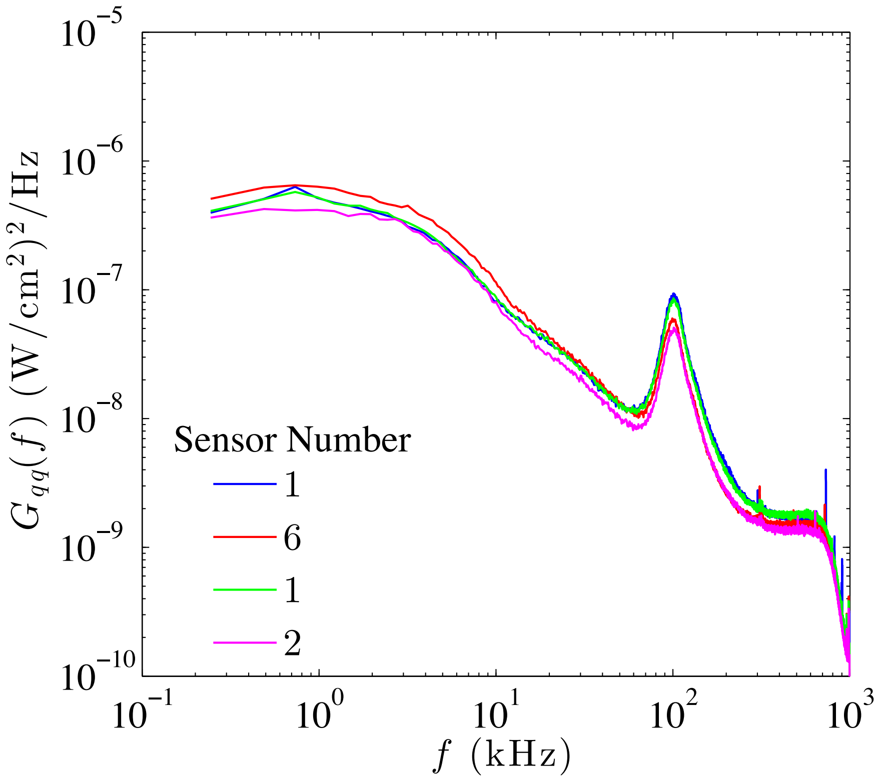
Measured wavelength for the most unstable second-mode disturbances



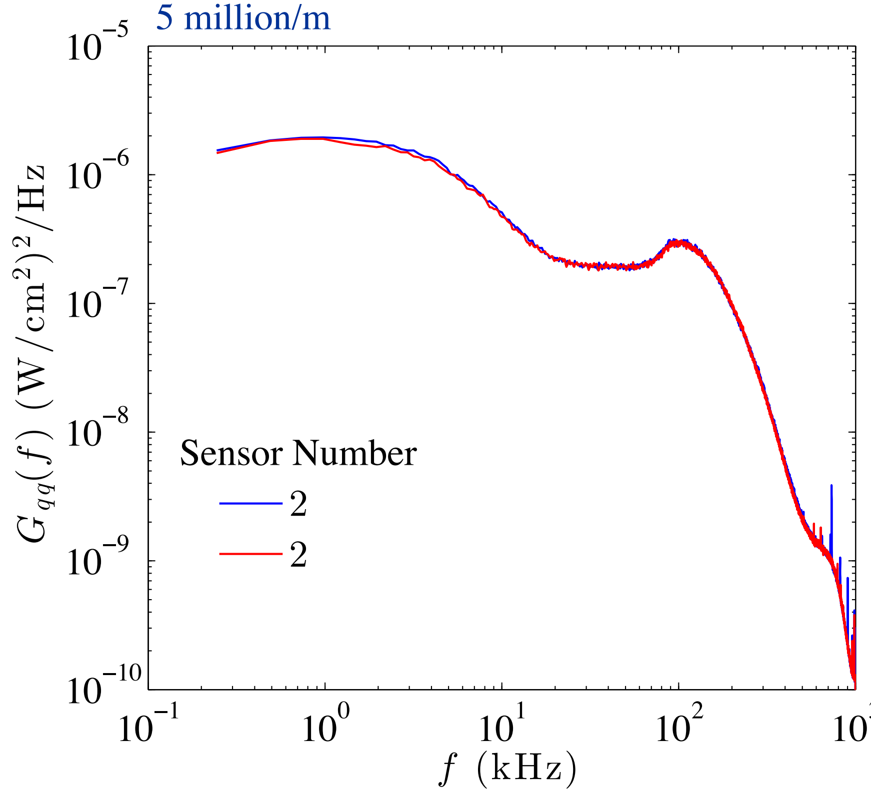
Note: The boundary layer thickness, δ, was based on the laminar similarity solution with a Sutherland viscosity model

Run-to-Run and Sensor-to-Sensor Repeatability

Heat flux power spectral densities measured with different sensors at x = 29.34 cm and a unit Reynolds number of 5 million/m



Heat flux power spectral densities measured with the same sensor in two different runs at x = 40.51 cm and a unit Reynolds number of 5 million/m



Issues with static calibration? Accuracy of static sensitivity?
How flush is sensor plug with model surface?

Summary

- Dynamic calibration via laser-based radiative heating
  - Frequency response of our ALTP sensors was 650 kHz
  - Sensor-to-sensor frequency response functions were nearly the same
  - Pre- and post-test measurements of frequency response functions were essentially the same

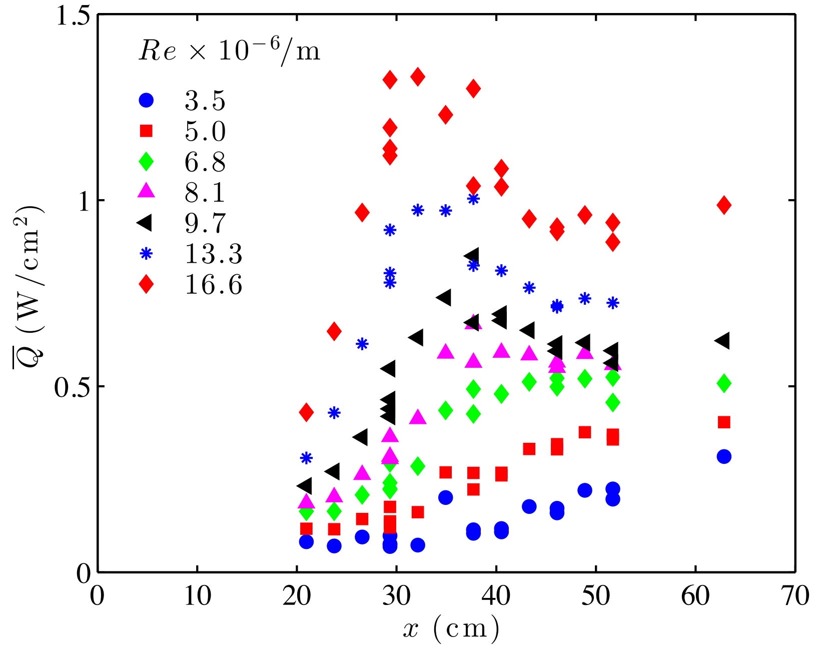
- Measurements of second-mode instability waves on a flat plate model in a Mach 6 freestream
  - Results are in-line with what we expect from theory and previous measurements
  - Most-amplified second-mode frequency varies inversely with boundary-layer thickness
  - Phase speed is roughly 90% of the freestream velocity
  - Instability wavelength is roughly twice the boundary-layer thickness

- ALTP sensor measurement repeatability
  - Run-to-run repeatability for a given sensor is acceptable
  - Sensor-to-sensor measurements at a given port location show some variability
  - How accurate is the static calibration?
  - How stable is the static calibration over time?
  - How flush is the sensor with the model surface?

Backup Slides

Heat-Flux Statistics

Mean Heat Flux



Broadband R.M.S. Heat Flux